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****ref chk, fig chk, table chk, section # chk, spell chk, smart quotes layout chk, ** chk**

****Vocab:** No more learned programs, we're dealing with intelligent assistants. In some cases, "adaptive software" seems appropriate as well.

****Vocab:** "data" is plural. So, need "data are" instead of "data is".

****Vocab:** It's a Why-oriented approach (capitalized)

****Vocab:** It's naïve Bayes (lower-case 'n')

****Vocab/numbering:** change the following globally:

Principle (i) -> Principle Representation-1

Principle (ii) -> Principle Representation-2

Principle (iii) -> Principle ML-1

Principle (iv) -> Principle ML-2

****Length:** TiiS suggests manuscripts be between 10,000 and 15,000 words.

Why-Oriented End-User Debugging of Naïve Bayes Text Classification^{*}

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Abstract **D2.5

Machine learning techniques are increasingly used in *intelligent assistants*, software targeted at and continuously adapting to assisting end users with email, shopping, and other tasks. Examples include desktop SPAM filters, recommender systems, and handwriting recognition. Fixing such intelligent assistants when they learn incorrect behavior, however, has received only limited attention. To directly support end-user “debugging” of assistant behaviors learned via statistical machine learning, we present a Why-oriented approach that allows users to ask questions about how the assistant made its predictions, provides answers to these “why” questions, and allows users to interactively *change* these answers to “debug” these assistants’ current and future predictions. To understand the strengths and weaknesses of the approach, we conducted an exploratory study to investigate barriers that participants would encounter when debugging an intelligent assistant using our approach, and the information those participants requested to overcome these barriers. To help ensure the inclusiveness of our investigation, we also explored how gender differences played a role in barriers and information needs. We then use these results to consider opportunities for Why-oriented approaches to address the users’ barriers and information needs.

1. Introduction **D2

Machine learning is increasingly being used to power *intelligent assistants*, software that continuously tunes its behavior to match a specific end user’s interaction patterns, so as to assist the user in getting work done (helping organize email, recommending books relevant to the user’s interests, typing hand-written notes, and so on). When assistants adapt themselves in helpful ways, the benefits are obvious: SPAM filters misclassify

fewer e-mails, recommendations find interests quickly, and handwriting recognition tools do a good job of typing up the user’s notes.

What happens, however, when a user’s assistant adapts itself in unhelpful ways? A straightforward answer might seem to be “provide more training examples,” but such an approach can be unrealistically time-consuming for an end user, and may not solve the particular misbehaviors the user cares most about. We posit instead that, just as with regular software, when an intelligent assistant fails, it should be possible to debug it directly. Further, since intelligent assistants do not return to the hands of programming specialists, the only people in a position to debug intelligent assistants are the end users themselves, because they are the only ones using that specific adaptation.

Enabling end users to debug their assistants is non-trivial: most users have little knowledge of how systems based on machine learning operate. Prior work, however, has shown that end users can learn to understand how a learning system makes its decisions [Tullio et al. 2007]. We therefore prototyped a new approach that aims to support end users in guiding and correcting—i.e., debugging—automated text classification. The domain we chose to explore was classification of e-mail messages into e-mail folders, as supported by the widely used naïve Bayes algorithm.

Our work makes three primary contributions. First, we present a new *Why-oriented approach* to allow end users to debug their intelligent assistants. The approach not only focuses on answering end-user questions about *why* the program is behaving in its current manner; it also provides interactive explanations that serve as a *debugging mechanism*. Because end users are directly debugging the assistant (as opposed to providing new training examples), our approach presents information that a programmer would expect when directly debugging other kinds of software: representations of both the intelligent assistant’s *logic* (i.e., its source code) and *runtime state*. The essence of the approach is simple: if the users do not like the explanations that answer their “why” questions, they can *change* the explanations to direct the assistant to behave more accurately.

Second, our work explores the difficulties experienced by end users attempting to debug an assistant in this Why-oriented manner. We present an exploratory study that identifies and categorizes *barriers* users encountered while debugging using a prototype based on our interactive approach. We also investigated both what *information needs* of

end-user debuggers expressed, and when they needed this information. Finally, because of recent evidence of gender differences in debugging (e.g., [Grigoreanu et al. 2008, Subrahmaniyan et al. 2008]), we investigated differences in barriers and information needs by gender to highlight design considerations that could differently impact these subsets of end users.

Third, we consider how to progress further with Why-oriented debugging by identifying *machine learning solutions* and *open research questions* as to how machine learning systems can address the information needs and barriers of end users attempting to debug their intelligent assistants.

2. Related Work **D2.9

As part of its support for debugging, our Why-oriented approach explains the logic of an intelligent assistant to end users so that they can understand how to debug it. There are thus two major classes of prior work: techniques that support end-user debugging, and techniques that support communication between users and machine learning systems. We next discuss each, identifying the foundations that informed the design of our own prototype.

2.1 End-User Debugging **D2.75

Outside of machine learning, there are a number of debugging systems that help end users find and understand the causes of faulty behavior. For example, in the spreadsheet domain, WYSIWYT [Burnett et al. 2003] has a fault localization device that helps users reason about successful and unsuccessful “tests” to locate cells whose formulas are likely to be faulty. Woodstein [Wagner and Lieberman 2004] helps users to debug e-commerce problems by explaining events and transactions between services.

The Whyline [Ko 2008] pioneered a method (also outside the realm of machine learning) to debug certain types of programs in an explanation-centric way. Because the Whyline informs our approach, we present it in some detail.

The original Whyline was explored in three contexts: event-based virtual worlds written in the Alice programming system [Ko et al. 2004], Java programs [Ko et al. 2008], and the Crystal system for debugging unexpected behaviors in complex interfaces [Myers et al. 2006]. In each case, the tools help programmers understand the causes of

program output by allowing them to select an element of the program and receive a list of *why* and *why not* questions and answers in response. These “Why?” questions and answers are extracted automatically from a program execution history, while “Why not” answers derive from a reachability analysis to identify decision points in the program that could have led to the desired output. In the Crystal prototype, rather than presenting answers as sequences of statement executions, answers are presented in terms of the user-modifiable input that influenced code execution. In all of these Whyline tools, the key design idea is that users select some output they want to understand, and the system explains the underlying program logic that caused it.

Some researchers have focused on the problems and needs end users encounter when they debug. For example, Ko et al. explored *learning barriers* that novice programmers encountered when learning how to solve problems in a programming environment [Ko et al. 2004]. Researchers from the WYSIWYT project have categorized the *information needs* of end users debugging [Kissinger et al. 2006], enumerating the types of information that end users sought in attempting to debug spreadsheets. These barriers and information needs may also relate to non-traditional debugging, such as fixing intelligent assistants. **MMB to anyone: R1 wanted more on Kissinger. Potentially this is the right place to put that, or perhaps it goes better later? (And if later, maybe we should hint at that here?) **TDK: I was planning on discussing this later, in the Information Needs section.

2.2 Communicating with Machine Learning Systems **D2.75

Several recent studies have highlighted the need to explain a machine learning algorithm’s reasoning to users. For example, Patel et al. examined obstacles faced by developers familiar with machine learning who need to apply machine learning to real-world problems [Patel et al. 2008]. Glass et al. investigated the types of questions users familiar with intelligent agents would like to ask an adaptive agent in order to increase their trust in the agent [Glass et al. 2008]. Similarly, researchers identified the types of information end users wanted context-aware applications to provide when explaining their current context, to increase both trust in and understanding of the system [Lim and Dey 2009].

Much of the work in explaining probabilistic machine learning algorithms has focused on the naïve Bayes classifier [Becker et al. 2001, Kononenko 1993] and, more generally, on linear additive classifiers [Poulin et al. 2006]. Explanation of these algorithms is relatively straightforward and computationally feasible on modern hardware. Tullio et al. reported that, given some basic types of explanations, end users can understand how machine learning systems operate [Tullio et al. 2007], with the caveat that overcoming any preliminary faulty assumptions may be problematic. More sophisticated, though computationally expensive, explanation algorithms have been developed for general Bayesian networks [Lacave and Diez 2002]. Finally, Lim et al. [Lim et al. 2009] investigated the usefulness of the Whyline approach for explaining simple decision trees and found that the approach was viable for explaining this relatively understandable form of machine learning.

Regarding allowing end users to actually *influence* behaviors in machine learning settings, some Programming by Demonstration (PBD) systems learn programs interactively, via machine learning techniques, based on sequences of user actions (see [Lieberman 2001] for a collection of such systems). When debugging these kinds of programs, end-user corrections are limited to the addition or removal of training data—unless the user reverts to a traditional programming language such as Lisp (e.g., [Vander Zanden and Myers 1995]). For example, Gamut allows users to “nudge” the system when it makes a mistake, leading to the addition or deletion of training examples [McDaniel and Myers 1999]. Recent work with PBD systems allows some debugging of programs [Chen and Weld 2008], but again, their technique only allows the user to retract actions in a demonstration, which results in adding missing values to the training data rather than directly modifying the classifier’s logic. Still other systems allow users to patch up specific mistakes by an intelligent assistant, but do not take these corrections into account when the assistant makes future decisions. For example, if CoScripter/Koala programs misidentify web page objects, the user can specify the correct object for a particular page; the fix, however, will not affect how the program identifies similar objects on different pages [Little et al. 2007].

Debugging—that is, directly changing the logic of—intelligent assistants has received only limited attention. One such system, EnsembleMatrix [Talbot et al. 2009], provides

both a visualization of a classifier’s accuracy and the means to adjust its logic. EnsembleMatrix, however, is targeted at machine learning experts developing complex ensemble classifiers, rather than end users working with the resulting classifiers. ManiMatrix [Kapoor et al. 2010] provides an interactive visualization of a classifier’s accuracy, but user interactions are restricted to the modification of a classifier’s cost matrix.

Our own prior research has begun to explore end-user interactions with intelligent assistants, to understand how to effectively enable end users to debug such programs. Using a paper prototype, we previously investigated three different types of explanations (keyword-based, rule-based, and similarity-based) that machine learning systems could provide to end users regarding why it was behaving in a particular manner, as well as user reactions to these explanations [Stumpf et al. 2007]. This paper prototype was also used to elicit corrections to the logic from participants (e.g., adjusting feature weights), allowing us to design an interactive prototype supporting the explanations best understood by participants and the types of corrections they most requested [Stumpf et al. 2008]. The interactive prototype permitted us to run offline experiments studying the effects of the corrections provided by end users on prediction accuracy versus traditional label-based corrections. The results suggest that even when very simple corrections are incorporated into the assistant’s decision-making process, it has the potential to increase the accuracy of the resulting predictions [Stumpf et al. 2008, Stumpf et al. 2009]. For some users, however, the quality of the assistant’s predictions decreased as a result of their corrections; there were barriers that prevented them from successfully debugging the assistant.

In summary, the ability of end users to interactively debug machine-learned logic has been limited. Researchers have begun to investigate how such logic can be explained to end users, but user corrections, if available at all, has been heavily restricted to specific forms (e.g., addition of training data) or situations (e.g., the initial creation of a new program via PBD). In addition to explaining the underlying logic, this paper also addresses supporting *end users* actually *fixing* the logic of a program learned by a machine.

3. A Why-Oriented Approach for Debugging Intelligent Assistants **D2

Inspired by the success of the Whyline’s support for debugging [Ko 2008, Myers et al. 2006] and favorable user feedback regarding “why” and “why not”-style explanations [Lim et al. 2009, Lim and Dey 2009], we developed a Why-oriented approach for end-user debugging of intelligent assistants. We applied this approach to the design of a prototype that allows end users to debug an assistant’s predicted folder classifications of an e-mail application.

Our approach is the first to combine the following elements:

- (1) it allows end users to ask questions directly to statistical machine learning systems (e.g., “why will this message be filed to ‘Systems’?”),
- (2) the answers to which explain both the current logic and execution state (e.g., a visualization that shows importance of features/words to this folder, and how certain the system is that it belongs in this folder) and
- (3) can be changed: users can *change* these explanations by direct manipulation, to debug the system’s logic. These changes result in real-time adjustments to the assistant’s logic and resulting predictions.

3.1 Design of the Why Questions **D2

Developing the set of why questions about the logic and execution state of the intelligent assistant comprised two stages. In the Generate stage, generated the set of all possible questions that could be asked via the creation of a formal grammar. Then, in the Filter stage, we filtered the set of questions generated by the grammar to remove impossible questions, where *impossible* refers to situations that were not related to or achievable by debugging an intelligent assistant. We chose this generate-and-filter approach, as opposed to handcrafting the questions ourselves, to be sure we would not miss any possible questions **2.12.

We began the Generate stage by inventorying the domain objects, such as messages and folders, which inform the assistant’s logic. We also inventoried, at a more abstract level, all logic (and corresponding runtime states) feeding into the prediction, such as the importance of a word to a folder. Finally, we inventoried the types of feedback the assistant could provide about its logic and execution state, such as its folder predictions

and its estimation of word importance. The first inventory (domain objects) is enumerated in the *Subjects* section of Table **QueryGrammar, and the latter two together are the *Situations* section of Table **QueryGrammar.

****MMB to Todd: I'd like to change "source code" to "logic" throughout -- ok? It makes the story line much easier to unravel...**

Step four relates to past, present, and future program states. Thus, we enumerated three question-word phrases -- *why is*, *why did*, and *how can* -- plus the negations of these

Table **QueryGrammar: The query grammar used to generate our Why questions.

Components	Productions
Questions	<ul style="list-style-type: none"> • Why...? • How...?
Verbs	<ul style="list-style-type: none"> • To be • To do • Can/Make
Modifiers	<ul style="list-style-type: none"> • This • All • Many • Recent • Important
Subjects	<ul style="list-style-type: none"> • Message • Folder • Word • Change • End user (i.e., "I")
Situations	<ul style="list-style-type: none"> • Current classification • Change in classification • Importance • Availability (i.e., displayed in the UI)
Queries	<ul style="list-style-type: none"> • [query] = [question] [verb] [subject] [situation] [question] [situation] [verb] [subject] • [situation] = [situation] [situation] [subject] [subject] [situation] • [subject] = [subject] [modifier] [subject] • [modifier] = [modifier] [modifier] [modifier]

phrases. We included “how can” questions to support debugging questions about future states of the system: when the system explains *why* it did something, the answer often implies *how* alterations could make the system do something different. We split these three question-word phrases into two non-terminals (*question* words and *verb* words) to make our *query* production more flexible. The *Questions* and *Verbs* sections of Table **QueryGrammar generate a super-set of these types of question-word phrases. Finally, in step five we added the *Modifiers* section to allow generated questions to be more specific, e.g., a question about *recently* changed predictions, rather than *all* changed predictions. The *Queries* section of Table **QueryGrammar describes how the various components may be combined to form the universe of possible questions.

For example, our grammar defines a possible query as “[*question*] [*verb*] [*subject*] [*situation*]”. Selecting the first listed production for [*question*], [*verb*], and [*subject*] produces the production “Why will this message [*situation*]?”. The first production for the *Situations* component (*current classification*) can then be substituted for [*situation*], resulting in the completed question, “Why will this message be filed to Enron News?”.

**1.3, **2.11

In the Filter stage, we filtered the questions generated by the grammar in three ways. First, we removed questions about subject/situation combinations that could not be accomplished by the intelligent assistant. For example, a message (a *Subject*) can change its current classification (a *Situation*), but words and folders (also *Subjects*) cannot. We further refined our list of questions by removing any questions not relating to debugging, such as “Why can important words be displayed?” Finally, we removed re-phrasings of similar questions; this explains why there are no questions beginning with “How can...”, since asking “*How can* I make something happen?” is answered by the same information provided by the “*Why didn’t* something happen?” questions. This decision is consistent with the results of [Lim et al. 2009], who found that participants were more successful reasoning about intelligent assistants in the form of decision trees when presented with answers to either “Why...” or “Why not...” questions, than participants were when presented with answers to “How to...” questions **1.3.

The Filter stage resulted in the nine Why questions depicted in Table **WhyQuestions. (While the number nine may seem small, the original Whyline

required only six types of questions [Ko 2008] in the complex domain of Java programming.) Figure **WhyQuestionsMenu shows how these questions were presented in the prototype, including their context dependency (such as the ability of the user to select questions relating to specific folders).

Table **WhyQuestions: The Why questions and the query grammar productions used to generate them. Color is used to map each non-terminal production to the terminal English phrase it generated. Text in < > is dynamically replaced with the word or folder the user has selected.

Why Questions	Generating Production
Why will this message be filed to <Personal>?	[question] [verb] [modifier] [subject] [situation] [subject]
Why won't this message be filed to <Bankruptcy>?	[question] [verb] [modifier] [subject] [situation] [subject]
Why did this message turn red?	[question] [verb] [modifier] [subject] [situation]
Why wasn't this message affected by my recent changes?	[question] [verb] [modifier] [subject] [situation] [modifier] [subject]
Why did so many messages turn red?	[question] [verb] [modifier] [subject] [situation]
Why is this email undecided?	[question] [verb] [modifier] [subject] [situation]
Why does <banking> matter to the <Bankruptcy> folder?	[question] [verb] [subject] [situation] [subject]
Why aren't all important words shown?	[question] [verb] [modifier] [subject] [situation]
Why can't make I this message go to <Systems>? ¹	[question] [verb] [subject] [modifier] [subject] [situation] [subject]

¹ The user interface moved the location of "I" in this question to fit the grammatical rules of English.

3.2 Design of the Interactive Why Answers **D2

In the original WhyLine, answers to “why” questions pointed to relevant places in the source code, but in intelligent assistants, there is no source code that represents the assistant’s learned logic for *end users* to look at or modify. Thus, the interactive answer content would have to represent the assistant’s logic by some device other than source code, while still allowing end users to edit it effectively to change the assistant’s logic.

Thus, we designed the interactive answers according to four principles:

Principle Representation-1: **2.6 Representations of both the assistant’s logic and execution state should be available to and manipulable by end-user debuggers.

Principle Representation-2: Explanations of the source code and execution state should not obscure or overly simplify the program’s logic.

Principle ML-1: The intelligent assistant should be explainable to end users.

Principle ML-2: The intelligent assistant should heed end users’ corrections.

Principle Representation-1 was inspired by the information content that traditional debugging systems provide. Such systems provide a representation of the logic (source code) that the programmer can edit. They also provide ways to inspect concrete data about program execution states. For example, debuggers provide access to the value of variables and the stack.

Principle Representation-2 boils down to being fully truthful with the user about the assistant’s logic. Machine learning often uses complex statistical models, so there is a

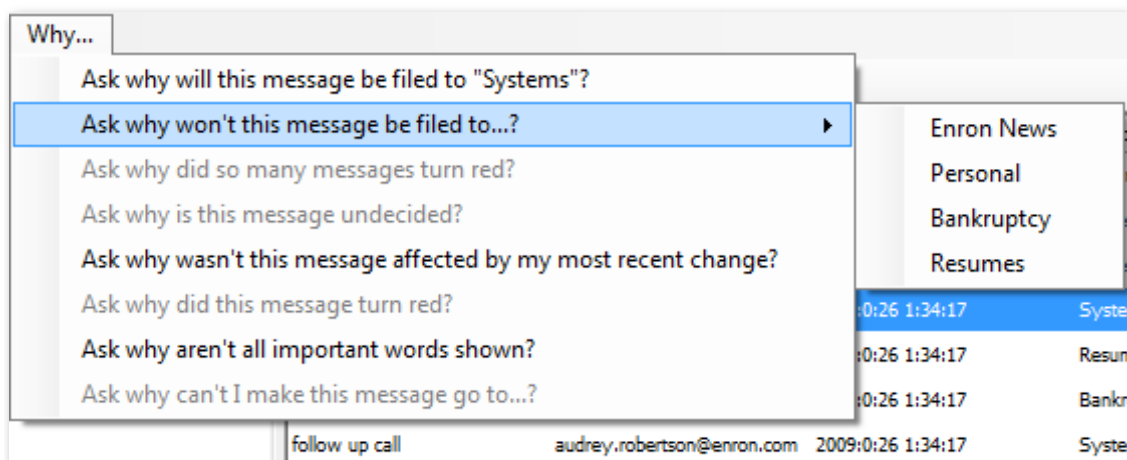


Figure **WhyQuestionsMenu: The Why questions as presented in our prototype.

temptation to hide complex details from the end user in an effort to make the system easier to understand. Recent research [Tullio et al. 2007], however, showed that end users could understand the logic machine learning systems use to make their decisions, at least in a rule-based system ****2.9**. Further, obscuring this logic would break the debugging “principle of immediacy” [Ungar et al. 1997] by creating an artificial division between the logic end users can view and interact with, and the underlying logic actually responsible for the assistant’s output. Thus, abstracting away portions of the assistant’s logic may hamper, rather than help, the user’s debugging efforts. ****1.2, **2.8**

Principle ML-1 is almost a corollary to Principle Representation-2. We wanted to support underlying learning algorithms more complex than the trivially explainable decision trees, but not algorithms so complex that supporting Principle Representation-2 would become impossible. Regarding Principle ML-2, we also required that the underlying learning algorithm must be responsive to the user’s interactive manipulations to the logic representation. We expand upon both of these points in the next subsection.

3.3 The Answer Design Principles and the Underlying Machine Learning Engine **D2? **MMB to WKW, pls chk wording of entire subsection.****

With these four design principles in mind, we chose the naïve Bayes [Russell and Norvig 2003] algorithm for our prototype. Naïve Bayes is a widely used algorithm for text classification, more complex than ordinary decision trees, yet seemed potentially explainable to end users (Principle ML-1).

The machine learning features in our e-mail prediction application were the words embedded in actual e-mail messages. Given our choice of naïve Bayes as the learning algorithm, these features and their associated predictive value for a classification are a complete representation of the assistant’s *logic*. The *execution state* of the assistant is therefore the current set of predictions resulting from this logic, including the assistant’s degree of certainty in each prediction. This application of Principle Representation-1 thus results in user-manipulable logic (words and their associated importance), changes to which affect the assistant’s execution state (its predictions and their associated confidence).

Although our previous work [Stumpf et al. 2007] found that rule-based explanations were the most easily understood type of explanation, Principle Representation-2

stipulates that the explanation should accurately reflect the logic of the assistant. Thus, given our use of naïve Bayes, we chose keyword-based explanations consisting of words and their weights. To implement Principle Representation-2, the visualization is a truthful reflection of the logic of naïve Bayes and hence displays the union of all words in all e-mail messages. We allowed users to adjust the weights of any word. Because naïve Bayes classifiers also use class distribution to inform their predictions, the distribution of messages across folders is also shown to the end user. Hence, the visualization and manipulations allow the user to directly change the logic the assistant should follow, based on an accurate representation of how the logic works.

Principle ML-2 says that corrections end users give the system should be heeded. We had considered using user co-training [Stumpf et al. 2009] as the underlying algorithm. When user co-training receives new information from the user about a feature’s value to a folder, this technique assigns a new weight, based on a *combination* of the user-assigned value and the classifier’s internal weight—which could potentially be quite different from the user-assigned value. In our previous work with user co-training [Stumpf et al. 2008], we observed that this behavior was frustrating to users because it made the algorithm appear to “disobey” the user’s corrections. Thus, instead of user co-training, we modified the naïve Bayes implementation such that corrections can be integrated in a straightforward manner and, when the user modifies the weight of a word, the classifier can set the new value to be close to the value specified by the user. **2.1

Being responsive to user corrections can be problematic because machine learning is *statistical*, and a single user correction may be such a small portion of data, the machine can appear to ignore it. When making the intelligent assistant heed the user’s correction, applying the user’s input directly could entirely discard the statistical aspect of machine learning, which is counter to our interest in improving the assistant’s intelligence (not discarding it). Naïve Bayes can, however, make a slight modification to the user-assigned weight by treating the user-specified folder assignment for the current e-mail as a new training data point for the classifier. This alteration makes the classifier more sensitive to user feedback in the interactive setting. Without it, changing the weight of one out of thousands of available features (e.g. changing the weight on one word out of the

approximately 6,000 different words contained in our email messages) would have little noticeable impact on classification.

3.4 End-User Debugging with Answers **D2

From these design choices, the answers took the following form. Textual answers are provided for all questions, giving high-level explanations about the logic of the assistant and general suggestions about how to debug the program, but three questions are also answered through detailed visualizations of the assistant’s logic: these answers formed the debugging mechanism for the end user.

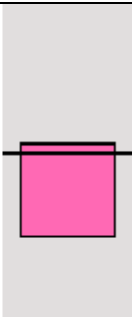
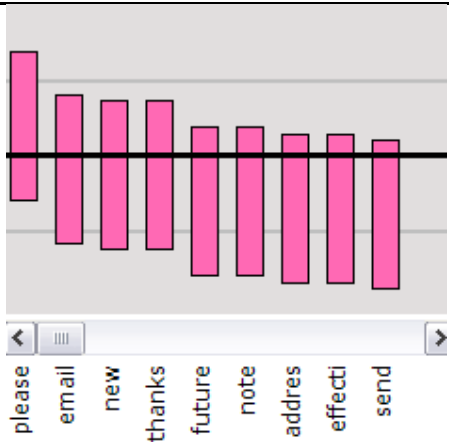

These answer visualizations are shown in Table **WhyAnswers. Similar to ExplainD [Poulin et al. 2006], bars represent the importance of each feature to a given classification. However, rather than using bar area to indicate a feature’s contribution toward the learning system’s prediction, we indicated importance via bar location. By changing a bar’s location, the feature’s weight can be adjusted in real-time **2.4, **2.5. The choice of bars, as opposed to points or some other representation, was because their large target size makes mouse-based interaction and visual discrimination easy. To debug the assistant’s faulty logic, users can change these answers by manipulating the bars, which operate like sliders or faders, with the weight of evidence represented by each bar being the midpoint of the bar **2.16.

Providing the necessary interactive aspect for these bar visualizations required support from the underlying machine learning algorithm. Before explaining how these visualizations were implemented, we formally define the following properties of the naïve Bayes algorithm. An e-mail message is represented as a “bag of words”, i.e., a Boolean vector $W = (W_1, \dots, W_m)$ in which W_i takes the value *true* if the *i*th word of a vocabulary of *m* words is present in the e-mail message and *false* otherwise. The vocabulary in our experiment consists of the union of the words from the following parts of all the e-mails: the message body, the subject line, and e-mail addresses in the ‘To’, ‘From’ and ‘CC’ parts of the message header. Stop words, which are common words with little predictive value (such as “a” and “the”) were not included in the vocabulary.

3.4.1 Answering: “Why will this message be filed in <Folder>?” and “Why does <Word> matter to <Folder>?” **D2

In previous work [Stumpf et al. 2007] we observed that end users understood how the presence of keywords influenced a message’s classification, but they struggled with the concept of how the absence of words influenced the same classification. We addressed this difficulty in a novel way by showing the weight associated with each word in the vocabulary via a bar positioned between the two extremes of *Required* and *Forbidden*, shown in the leftmost images of Table **WhyAnswers. For folder f , the weight of a word is the probability $P(W_i = \text{true} \mid F = f)$ where W_i is the random variable for the i th word and F is the random variable for the folder. The closer the bar is to *Required*, the more important the presence of the word is to the prediction. If the top of the bar is at its highest position, then $P(W = \text{true} \mid F = f) = 1.0$. If the top of the bar is on the black line in the middle, then $P(W = \text{true} \mid F = f) = 0.0$. Since $P(W_i = \text{false} \mid F = f) = 1.0 - P(W_i = \text{true} \mid F = f)$, the position of the bottom of the bar can also be interpreted as the probability of the absence of the word. If the bottom of the bar is at its lowest position, (i.e. closest to *Forbidden*), then $P(W = \text{true} \mid F = f) = 0.0$. In reality, although the end user is able to set the bars to its highest or lowest positions, the probability $P(W \mid F = f)$ is never set to the extreme values of 1.0 or 0.0 due to the naïve Bayes algorithm’s use of Dirichlet priors to smooth the probabilities. As a result, the probabilities will be an epsilon different from

Table **WhyAnswers: Visual explanations for three Why questions.

Why does <word> matter to <folder>?	Why will this message be filed to <folder>?	Why won’t this message be filed to <folder>?
<div>Required</div>  <div>Forbidden</div>		

the extremes and the bar will be positioned slightly below / above the Required / Forbidden level in the visualization.

Aside from the probability $P(W / F)$, the naïve Bayes classifier also uses the class probability $P(F)$. We chose not to display $P(F)$ because the training set consisted of an equal number of emails in each folder.

3.4.2 Answering: “Why won’t this message be filed in <Folder>?” **D2

The answer to this question is in the form of a dual-bar view that allows the user to compare and contrast the importance of words between the two folders, shown in the right image of Table **WhyAnswers. The bars show the respective weights for the currently predicted folder f , and the other folder f' the user indicated, where the positions of the bars correspond to $P(W_i = \text{true} / F = f)$ and $P(W_i = \text{true} / F = f')$, respectively.

We can illustrate the degree that an e-mail “belongs” to either folder f or f' using the arrow, as shown at the top of Figure **DebuggingFeatures. The angle of the arrow between the folders is based on the difference between $P(F = f' / W_1, \dots, W_m)$ and $P(F = f / W_1, \dots, W_m)$. This also serves to reveal the execution state to the end user. Since the bars allow weights associated with the two folders f and f' to be manipulated, changes to individual words by the end user that result in $P(F = f' / W_1, \dots, W_m) > P(F = f / W_1, \dots, W_m)$ will be shown by the arrow moving to point to folder f' instead.

3.5 Debugging Scenario Using the Prototype **D2

Figure **Prototype shows how the debugging supports we have described are brought together in our email prototype. The user’s view consists of familiar e-mail client elements: a folder list (A), a list of headers in the current folder (B), and the current message (C). In addition, it includes debugging panes that hold textual answers (D) and interactive visualizations (E).

If at some point the user wants to know why the program is behaving in a particular way, she can ask Why questions either through the global menu bar or a context-sensitive menu and receive an answer which supports debugging. Consider the following scenario: A user notices that her intelligent assistant thinks a message about *Systems* belongs in the *Resumes* folder. In Figure **DebuggingFeatures, this user has just asked why the message is not filed under *Systems*. The keyword bar graph shows the system's opinion of the importance of each word to the *Resumes* folder (dark pink), which is the current folder for this message, versus importance to the *Systems* folder (light blue). While reviewing this explanation, the user quickly identifies a problem—her assistant thinks the word “please” is equally important to both folders. The user disagrees; she wants to tell her intelligent assistant that she rarely sees the word “please” in messages from the *Systems* group. Thus, she drags the light blue bar lower (second from left); how much lower depends on her assessment of how important “please” should be to the *Systems* folder. The dark blue bar indicates the original importance of “please”, allowing the user

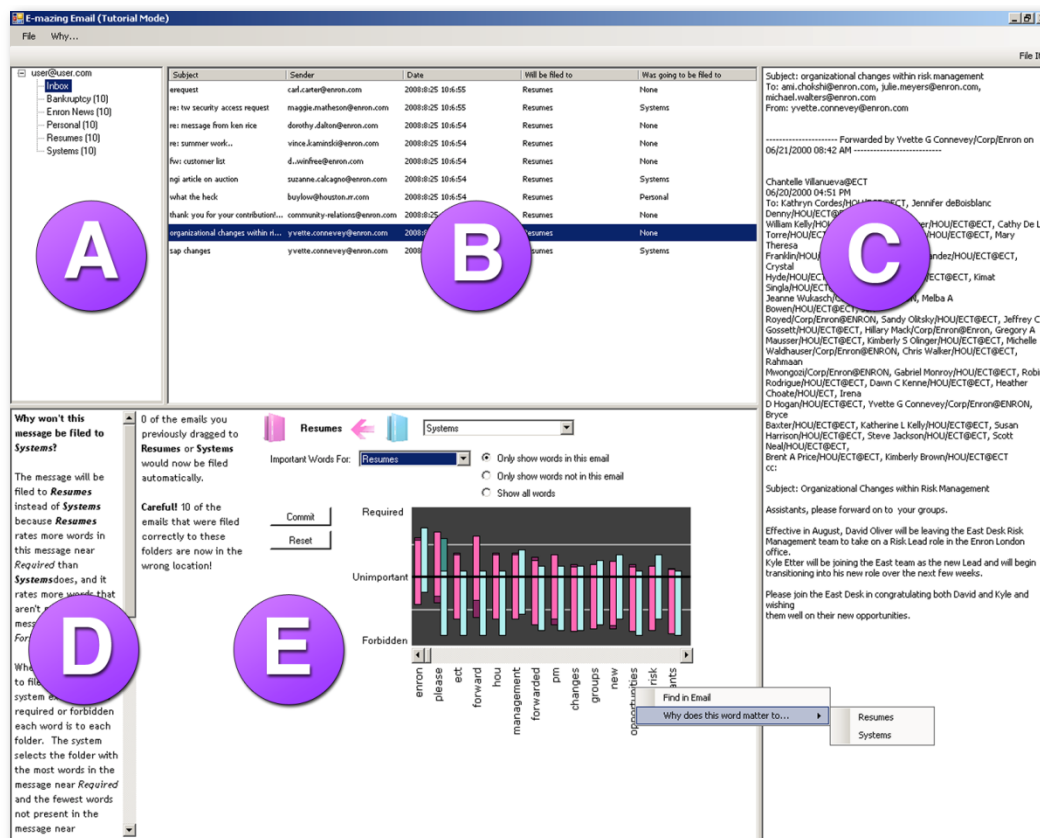


Figure **Prototype: Screenshot of the prototype.

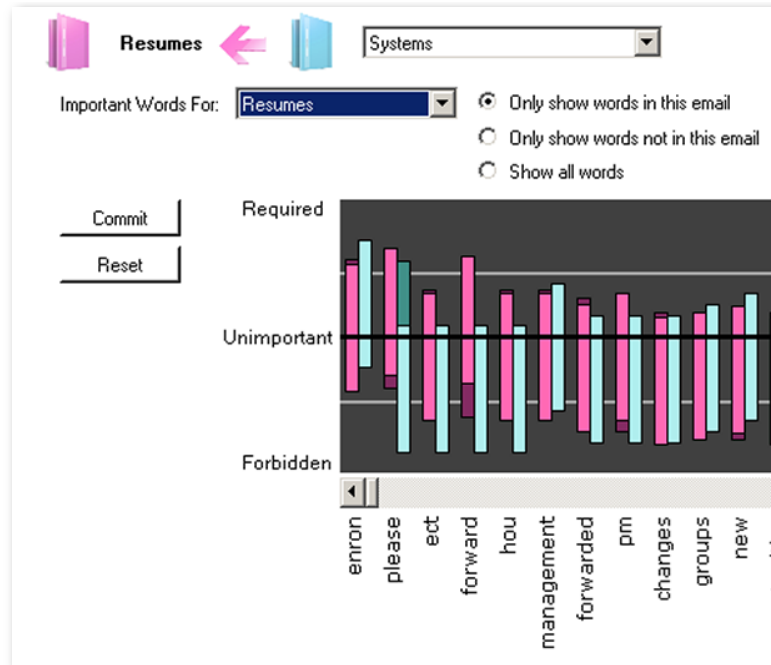


Figure **DebuggingFeatures: Close-up of the visualization/debugging features. The user has just decreased the importance of “please” to *Systems* by dragging the blue (light) bar downward, but the system still thinks the message belongs in *Resumes*.

to see her change and its magnitude. ****3.2**

User changes to each bar graph entry cause the system to immediately recalculate its predictions for every message in the inbox, allowing users to instantly see the impact of their manipulations. These changed folder predictions are shown through a change in direction of the arrow between the two folders for the currently viewed message. They are also listed textually next to each message header in the inbox, highlighting headers whose predictions have changed. For every manipulation, the user immediately sees how both the source code (in terms of the importance of words), and the execution state (e.g., the resulting program’s predictions), have changed.

4. Addressing Debugging Barriers and Information Needs using the Why-Oriented Approach **D1

To investigate obstacles end users might encounter while correcting an intelligent assistant using this new approach, we conducted an exploratory study using the prototype we have just described. Our purpose was not a summative evaluation of the prototype, but rather to investigate three questions to understand how our approach could be

extended to further support end-user debugging: *when* and *where* end-user debuggers encounter problem areas (barriers), *what* could help users when they encounter these problem areas (information needs), and *how* machine learning algorithms could help address the barriers and information needs. Further, since researchers have recently found evidence of gender differences in debugging, we investigated gender as an aspect to highlight design considerations that could differently impact subsets of end users.

4.1 Exploratory Study Design

4.1.1 User Study Design and Participants **D1

The study used a dialogue-based think-aloud design, in which pairs of users talked to each other while collaborating on a task. The pair design was to encourage “thinking aloud” by leveraging the social norms that encourage people to voice their reasoning and justifications for actions when working with a partner.

Six pairs of female and five pairs of male students participated. The pairs were evenly distributed by gender across GPAs, years in university, and e-mail experience. All twenty-two participants were required to have previous e-mail experience and no computer science background. In order to eliminate a lack of familiarity with each other as a potential confound, pairs were required to sign up together. Pairs also had to be same-gender, so that we could clearly identify any gender differences that might arise.

We ran the study one pair at a time. Each session started with the participants completing a questionnaire that asked for background information and gathered standard pre-session self-efficacy data [Compeau and Higgins 1995]. We then familiarized the pair with the software and examples of classification through a 20-minute hands-on tutorial. The tutorial taught participants about the filing and classification abilities of the prototype, taught them how to ask the prototype questions, and gave an overview of the the prototype’s answers and how to change those answers **3.2.

For the study’s main task, participants were asked to imagine they were co-workers in a corporate department at Enron. Their department included a shared e-mail account to provide easy access to work communications that affected all of them. The premise was that new e-mail software, featuring the ability to learn from the users and automatically classify messages into a set of existing folders, had recently been installed; their supervisor then asked them to get messages from the Inbox into the appropriate folders as

quickly as possible, doing so in a way that would help improve later classification. Because the prototype's classifier did not train on (and thus, did not learn from) messages the participants manually dragged to folders, the task encouraged participants to debug the system via the interactive explanations ****3.2**.

We used the publicly available Enron e-mail data set in our study. To simulate a shared mailbox, we combined messages that three users (farmer-d, kaminski-v, and lokay-m) had originally filed into five folders (Bankruptcy, Enron News, Personal, Resumes, and Systems). At the start of the session, each folder held 20 messages that were used to initially train the classifier. Participants were given five minutes prior to the main task to familiarize themselves with the existing categorization scheme, so that they would have an idea of how new messages should be filed ****3.2**, ****3.4**. The Inbox contained 50 more messages for the participants to work on. The amount of training data was small to simulate real-world situations in which users have not invested the time to label hundreds of training examples.

The pair worked on the main task for 40 minutes, with participants switching control of the mouse half way through the session. We used Morae software to capture video and audio of each user session, synchronized with their screen activity. Our prototype also logged each user action. After completing the main task, participants individually filled out a questionnaire gathering feedback about the prototype and their post-session self-efficacy.

4.1.2 Analysis Methodology **D1****

To analyze the participants' verbal protocol during our study, we developed two code sets (Table ****BarrierCodes**) to capture barriers and debugging activities. Ko et al. identified six types of learning barriers experienced by novice programmers using a new programming environment [Ko et al. 2004]; these barriers informed our investigation because our participants, like theirs, were problem-solving about how to make programs work correctly and were inexperienced with the provided facilities for debugging. Because our debugging environment is substantially different than the traditional textual programming environments studied [Ko et al. 2004], we adjusted the definitions of Ko's barriers to map the high-level problems each barrier describes to the problems participants faced while debugging with our prototype ****2.2**, ****3.5**:

- *Design barriers* are situations where the end user does not know what they want the computer to do. When debugging an intelligent assistant, this means the user doesn't have a clear idea of how to go about fixing the assistant.
- *Selection barriers* occur when the end user knows what they want the computer to do, but does not know which programming tools will accomplish their goal. Our why-oriented approach's programming tool is the ability to adjust the assistant's logic via feature modification, so we mapped selection barriers to end user difficulties in selecting which feature to adjust.
- *Coordination barriers* are times when the user knows the programming tools they want to use, but does not know how to make them work together. As with selection barriers, our programming tool is the ability to modify the features the assistant uses to classify items; such feature adjustments may alter multiple classifications. Thus, coordination barriers in this domain reflect the difficulty of coordinating how changes to the assistant's logic are reflected in updated classifications.
- *Use barriers* are situations where the end user knows which programming tools they want to use, but does not know how to use them properly. Our approach's UI affordance for feature modification is to drag a slider up (to increase the importance of a feature's presence) or down (to increase the importance of a feature's absence). Trouble deciding in which direction and to what extent to adjust this slider is our approach's version of use barriers.
- *Understanding barriers* occur when end users thought they knew what to do, but the results of their actions was surprising. This barrier very cleanly mapped to situations where the end user was surprised by the assistant's feedback.

The first five barrier names and examples of participant utterances assigned to each code are in Table **BarrierCodes. We did not use Ko et al.'s sixth barrier (searching for external validation), because problem solving in our study was based on facts internal to our environment. Regarding debugging activities, previous research [Davies 1996, Ko

2008] identified six common actions in fixing bugs in programming environments. We applied the two of these not involving data structuring or writing new source code, and also introduced a fault detection code. These codes are also given in Table

Table **BarrierCodes: Coding scheme used to analyze our data. The examples are from actual participant transcripts **3.5.

	Code	Meaning	Example
Barriers	Design	Uncertainty regarding overall debugging strategy (i.e., designing a solution to the problem).	“Can we just click File It?”
	Selection	Knows what to do, but is having trouble selecting which object to change.	“What kind of words should tell the computer to [file this] to Systems?”
	Coordination	Doesn’t understand how changes affect the rest of the system.	“Why... why it won’t go to Personal...”
	Use	Trouble determining appropriate weights to use with the source code visualization.	“So is [this word] ‘unimportant’?”
	Understanding	Doesn’t understand the system’s feedback.	“Why is ‘web’ more forbidden for [the] Systems [folder]?”
Debugging Activities	Fault Detection	Detecting an incorrect prediction by the system.	“It’s going to [the] Systems [folder]; we do not want Systems.”
	Diagnosing	Diagnosing the specific cause of a detected fault.	“Well, ‘e-mail’ needs to be higher.”
	Hypothesizing	Hypothesizing a general solution for a detected fault.	“Let’s move something else, and then maybe it’ll move [the e-mail] to Systems.”

**BarrierCodes.

We applied the codes to “turns”. A turn consisted of sentences spoken by a participant until his or her partner next spoke. Speech by one participant that contained a significant pause was segmented into two turns. If the same barrier spanned multiple

turns (for example, if one person was interrupted by the other), only the first occurrence of the barrier was coded. Only one code could be applied per turn.

Coding iteratively, two researchers independently coded a 5-minute random section of a transcript. We calculated similarity of coding by calculating the Jaccard index, dividing the size of the intersection of codes by the size of the union for each turn, and then averaging over all turns. Disagreements led to refinements in coding rules that were tested in the next coding iteration. Agreement eventually reached 82% for a five-minute transcript section, followed by an agreement of 81% for a complete 40-minute transcript. Given this acceptable level of reliability, the two researchers divided the coding of the remaining transcripts between themselves. A two-minute section of a coded transcript is include in Table **CodedTranscript to illustrate the application of our final code set.

Table **CodedTranscript: Example of our code set applied to a participant transcript **3.5.

Time	Participant	Utterance	Code
11	P1	And then... [looking at another email] should this be in Personal? It'll be all right. EOL...dist-dist-distributions? How come everything is going to Personal?	Coordination
11	P2	Because we filed to Personal last time. The system learned from other email. [clicks on 'windows 2000/outlook delay'] But this email should go to...systems. So would we have to change every single one?	Selection
12	P1	Did we do something wrong in the beginning?	Design
12	P2	I think this one can go to Personal.	
12	P1	Do we have to change the same thing again? Can we drag? If we drag we have to do it for every one.	
12	P2	Do we need to make them learn everything?	Design
12	P1	But I don't want to have to do it every time so like in next 10 minutes.	
12	P2	So you adjust every single message.	Hypothesizing
12	P1	Or maybe just this one. Maybe it will learn...I don't know.	Hypothesizing
13	P2	[ask 'why won't this message be filed to systems' and sorts words alphabetically. Finds 'windows'] Oh look it should be	Diagnosing

		important but it's not. [drags 'windows' up to increase importance] But I don't think we'll need that one that long. So can you go back?	
13	P1	Are you sure it's enough?	Use

4.2 Results: Debugging Barriers (*When and Where*)

4.2.1 Barriers Encountered **D1

Our participants' attempts to debug ran into numerous barriers, encountering an average of 29 barriers during the 40-minute study (with a range from 7 to 66). The number of barriers encountered can be contrasted with the number of messages participants actually filed (mean=16.1, SD=8.3); participants were less likely to encounter a situation where they felt comfortable filing a message than they were to encounter an obstacle while attempting that task **3.4. These barriers were equally likely to be encountered at the beginning and end of the study, but were unequally encountered between participants: a strong relationship existed between participant self-efficacy and the number of barriers they encountered (normalized for the number of utterances each participant made) (linear regression, $F(1,9)=7.11$, $R^2=0.44$, $\beta=-0.005$, $p=.026$) **3.4. Everyone hit barriers, and the participants who encountered them the most had the lowest confidence in their ability to fix the assistant to begin with, thus underscoring the importance of addressing these barriers in approaches for debugging intelligent assistants.

As Figure **BarriersEncountered shows, the most frequent barriers our participants encountered were *Selection* barriers (40% of all barriers). *Selection* barriers relate to the difficulty of selecting the right words or messages to modify in order to correct the program. In Ko et al's work [Ko et al. 2004] on traditional programming environments, *Selection* barriers did not play a large role, but this kind of barrier seems to pose a substantial problem to debugging intelligent assistants. This participant, for example, was having trouble determining which features are important for the *Systems* classification:

**1.4

P712: "Then 'news'? Well, they like team players. Contributions? That would be more that you'd use for news than Systems."

Coordination barriers also arose frequently (28% of all barriers). Participants often wondered how the corrections they were about to give would change the system's other

predictions, as well as coordinating how the system responded (or failed to respond) to their source code modifications:

P732: “Resume? [user finds word, makes ‘resume’ required] Why didn’t it change it?”

Further evidence that *Selection* and *Coordination* barriers were especially problematic comes from participants’ questionnaire responses, where 16 of 22 respondents (72%) mentioned difficulty in determining which words were important when fixing misclassified mail.

Some barriers encountered frequently in traditional programming environments did not play as much of a role as expected in debugging intelligent assistants [Ko et al. 2004]; our findings also contradict specific problems with strategy in end-user debugging [Kissinger et al. 2006]. Our participants ran into *Design* and *Use* barriers less frequently (14% and 12%, respectively), possibly because debugging via our approach involved programming constructs (i.e., feature adjustments) which only had two options—a feature could be made either more or less important. Both [Ko et al. 2004] and [Kissinger et al. 2006] explored programming environments with a wider array of available constructs (Visual Basic .NET and spread sheet formulas, respectively). Their participants may thus have had more opportunities to strategize about their debugging approaches, and we would expect recalling the proper usage of each programming construct to be more difficult than the two options (e.g., dragging a bar up or down)

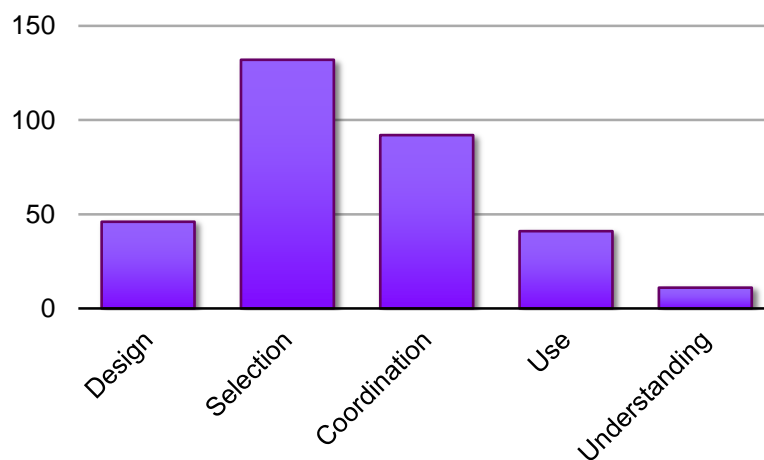


Figure **BarriersEncountered: Sum of barriers encountered in all transcripts.

available to our participants. While *Design* and *Use* barriers should not be neglected, the predominance of *Selection* and *Coordination* barriers in this domain suggests that end users may have less trouble deciding on a strategy for *how* to give feedback (*Design* and *Use*), than on *where* to give feedback (*Selection* and *Coordination*) ****1.5**.

Our results highlight that the kinds of barriers encountered while debugging intelligent assistants may be rather different than those seen in traditional programming environments, and hence require their own specialized support. Our Why-oriented approach provides explanations of source code and execution state, but the prevalence of the *Selection* and *Coordination* barriers suggests the need for debugging approaches to also help users identify the most useful places to change the source code (fault localization) as well as explaining the likely effects of executing such changes (run-time outputs).

The differences between the barriers our participants encountered and those faced by Ko's participants may also be related to differences in the programming environments. Our why-oriented approach included many instances of a single programming construct (feature importance); participants had relatively few problems using or understanding the results of interaction with this construct, but a great deal of difficulty in selecting which instances of the construct to interact with. The integrated logic of machine learning systems may have further contributed to these obstacles, causing confusion when multiple predictions changed as a result of a single feature modification. Our prototype's design may also have played a role: by showing feature weights in the context of particular messages, participants may not have expected adjustments to impact the assistant's other predictions. Even if participants *did* expect such wide-ranging changes, the difficulty of coordinating which and how many predictions changed in response to each user modification seems an innate issue with intelligent assistants—regardless of the underlying learning system, there are multiple possible “fixes” to the logic that will result in a particular item changing its classification. If a user is focused on a single prediction, this reduces their search space by providing many possible targets. However, finding the precise fix that both adjusts the item as desired and does not negatively impact other predictions may be considerably harder than in environments where each programming change is isolated to a single section of the application's logic. Such a situation would

explain why our participants often encountered Selection and Coordination barriers, while Ko's most frequently hit Use and Understanding barriers ****2.3**.

4.2.2 Gender Differences in Barrier Encounters **D1

Are barriers different for male and female end-user debuggers, and will overcoming them require different kinds of support? Interestingly, males and females did not appear to experience the same number of barriers: females encountered an average of 33.3 per session, versus the male average of 24.4 per session. This difference was despite the fact that males talked more (and thus had more opportunities to verbalize barriers) than females, averaging 354 turns per session, compared to 288 for females.

Figure ****AverageBarriers** shows the average barrier count per session (the same differences are also present in comparing the average barrier counts per turn). Females experienced more barriers in almost every category; the only exceptions were *Coordination* and *Understanding*. *Selection* barriers, the most common barrier type, had a large difference: females averaged 14 per session, about 1.5 times as many as the male average of nine. This difference was statistically significant despite the small size of our sample population (Wilcoxon Rank-Sum Test: $Z = 2.1044$, $p < 0.05$). *Design* barriers, too, exhibited a strong contrast, with females averaging 5.3 per session versus males averaging 2.8. The differences in both the total number of barriers and *Design* barriers encountered were not statistically significant, but this may be a result of our small sample size (totaling six female and five male pairs). A statistically oriented experiment with a larger sample is needed to provide more conclusive evidence.

One reason for the apparent differences may be that females expected more problems due to lower self-efficacy (a form of self-confidence specific to the expectation of succeeding at an upcoming task [Bandura 1977]). As referenced earlier, there was a significant, inverse correlation between self-efficacy and the number of barriers a participant encountered. Females came into the study with lower self-efficacy (measured via a self-efficacy question set [Compeau and Higgins 1995]) than males, scoring an average of 38 out of a possible 50, compared to 42 for males (Wilcoxon Rank-Sum Test: $Z = -2.64$, $p < .01$). This is consistent with similar self-efficacy differences for end users engaging in other complex computer tasks [Beckwith et al. 2005, Grigoreanu et al. 2008, Subrahmanian et al. 2008]. As we show in the next section, our results about differences

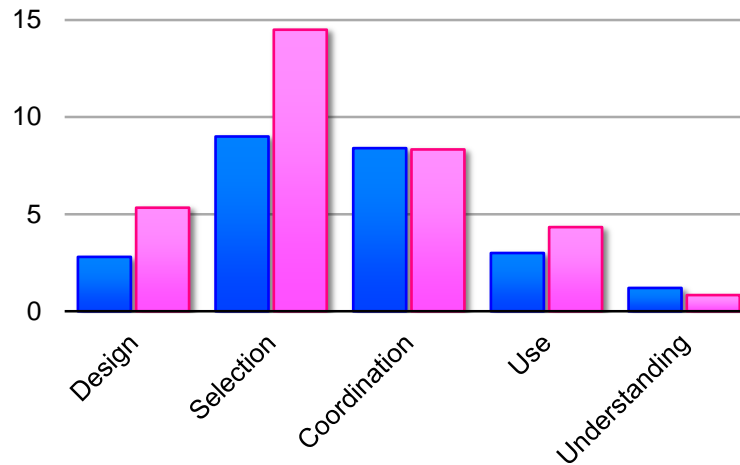


Figure **AverageBarriers: Average number of barriers per session encountered by males (dark blue bars) and females (light pink bars).

in barriers are consistent with prior research in another aspect as well: these prior works showed gender differences in both features used and the strategies end users employed to find and fix errors in spreadsheets.

Another possible cause of the observed disparities may be gender differences in information processing. For example, work on the selectivity theory of information processing [Meyers-Levy 1989] has shown a number of differences in how males and females process information. According to this theory, females are more likely to work with information comprehensively, whereas males are likely to pursue information more selectively. The following quotes illustrate the tendency our female pairs showed toward examining several words from a message before moving on, versus males' propensity for advancing to the next message as quickly as possible:

Female Pair

P1131: "So that [word is] really important. And then, um, probably 'updates' would be important. And then, um... [the word] 'virus'?"
P1132: "Yeah. And then, uh, [the word] 'login'."

Male Pair

P1211: "Its [classification is] correct. It's learned something, eh."
P1212: "Um hmm."
P1211: "Lets go to the next message."

The selectivity theory is also consistent with our frequency data: females worked with a larger set of words than males did (106 unique words for females vs. 62 for males), perhaps to perfect the algorithm's performance. Males, conversely, may have been more inclined to move on to the next message as soon as they obtained the desired effect. Supporting this hypothesis is the average number of messages each group filed—male pairs averaged 19.8 messages filed in each 40-minute session, while female pairs averages 13.0. This suggests that in order to successfully support a wide range of end users, debugging features should be designed so that both of comprehensive and selective strategies can lead to success ****1.6**.

4.2.3 Barrier Transitions and Gender Differences **D1****

When a participant encountered a barrier, what happened next? Were there different patterns of what male and female participants did after a hitting barrier? Encountering a barrier may have sent participants spiraling into non-productive repetition, or maybe they were able to overcome the barrier by themselves. Understanding how barriers are encountered and resolved (or not) can provide insight into their severity and impact on debugging intelligent assistants, and highlight when additional support may be most necessary.

To answer these questions, we investigated the sequence of barriers encountered and looked for differences between male and female participants. The barriers and debugging activities coded in participants' verbalizations are simply states between which they can transition. To calculate the probability of each state (barrier or activity) following an initial barrier, we divided the number of occurrences of a particular subsequent state by the total number of states that followed the initial barrier. For example, if *Selection* followed *Design* once and *Diagnosing* followed *Design* twice, then the probability of *Selection* following *Design* was computed as $1/(1 + 2) = 0.33$, or 33%, and the probability of *Diagnosing* following *Design* was computed as $2/(1 + 2) = 0.66$, or 66%. We use these probabilities only for clarity; our graphs (Figures ****Transitions1**, ****Transitions2**, ****Transitions3**, and ****Transitions4**) show the exact number of instances for completeness.

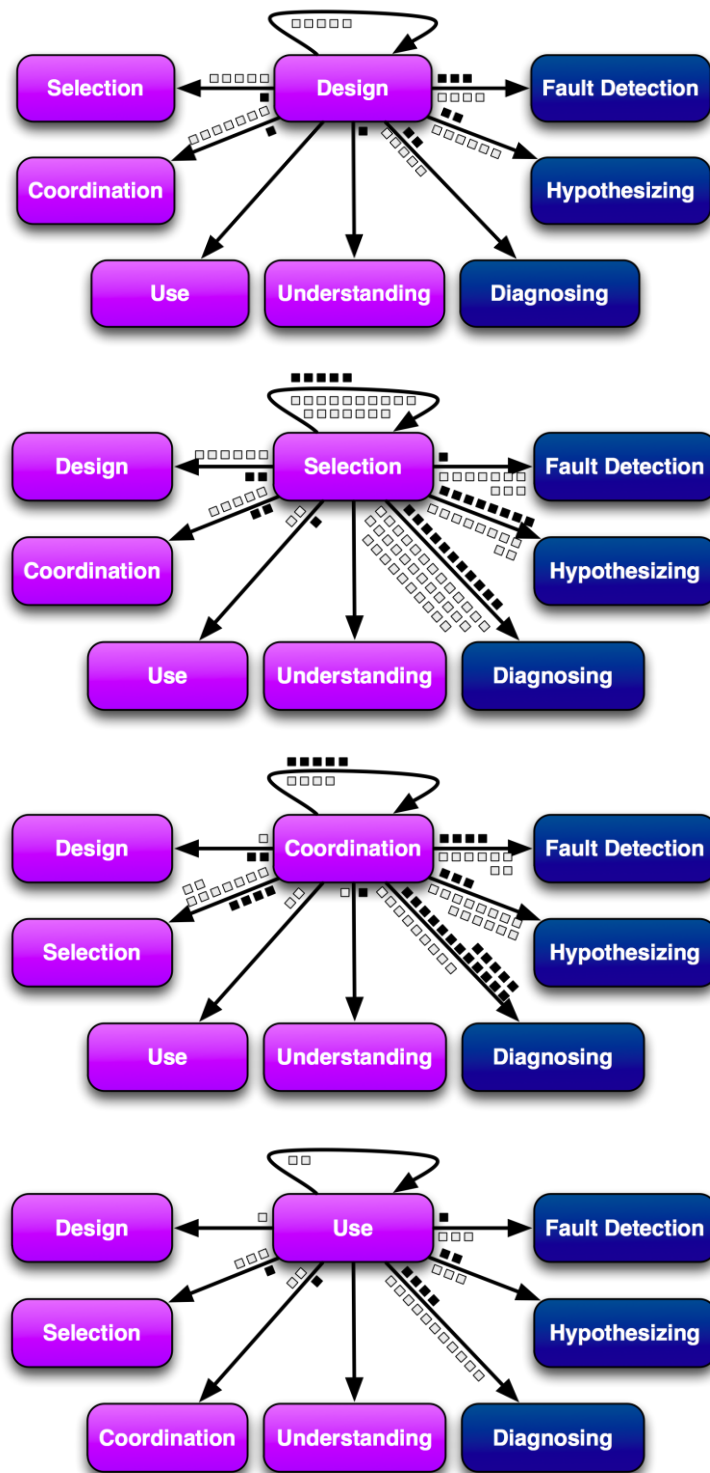
Initially, we hypothesized that there would be a commonly followed path through the barriers, which could allow us to support debugging at the right time. For example,

perhaps most users would flip between *Design* and *Understanding* barriers at the beginning of the task. Once those early hurdles were overcome, they might cycle through *Selection*, *Coordination*, and *Use* barriers until they understood the assistant's logic, after which barriers would be encountered with considerably less frequency. When examining our participants' data, however, we saw no discernible tendency for users to encounter barriers in specific orders or at consistent times during their debugging session. Nor did barrier frequency change in any significant way over time; users were just as likely to encounter *Design* barriers in the first five minutes of the study as they were in the final five minutes. This suggests that an approach aiming to support end-user debuggers in overcoming barriers must support finer-grained patterns of barriers *as they are encountered*, instead of basing its explanations on an expected common path.

Both male and female end users exhibited finer-grained patterns for many of the individual barriers. Although no single barrier stood out as a frequent transition from *Design* (Figure **Transitions1), when we examined gender differences, we found that males reacted to *Design* barriers with some form of debugging activity on average 70% of the time, versus 46% for females. Thus, it appears that *Design* barriers proved less of a problem to males than females, since they were able to move on to a debugging activity instead of encountering another barrier. Since *Design* barriers relate to a user lacking a debugging strategy, an implication of this gender difference is that our approach's explanations for overcoming these barriers should be certain to include strategies other researchers have identified as frequently employed by female end-user debuggers [Subrahmaniyan et al. 2008].

Figure **Transitions2 shows that the most common action following a *Selection* barrier was the debugging activity *Diagnosing*, which occurred after 40% of *Selection* barriers. The next most prevalent code was a second *Selection* barrier (19%), suggesting that *Selection* barriers were either quickly overcome, leading to *Diagnosing*, or they cascaded, stalling participants' debugging progress. This implies that once a user first had trouble deciding where to give feedback, they became less and less able to do so. Figure **ExampleTransitions illustrates the problem by graphing all of the barrier transitions for one of our participant pairs (P701 and P702). The high number of incoming edges to the *Selection* box was typical, as is the loop from *Selection* back to itself. We already

discussed the high number of *Selection* barriers overall, but Figure **Transitions2 points to these barriers specifically *stalling* participants. This suggests the need for our approach to point out which words or features would be most likely to change the program's behavior; we discuss how this might be done in Section 4.4.1. These participants, for example, could have benefited from this sort of help:



Figures ****Transitions1**, ****Transitions2**, ****Transitions3**, and ****Transitions4** (from top to bottom): Number of transitions from barriers to other barriers or debugging activities. Light squares indicate one instance by a female pair; dark squares indicate one instance by a male pair. Barrier nodes are colored light purple; debugging activity nodes are dark blue.

P732: "And what about 'interview'? Oh, we just did that, so no.
 'Working', maybe?" [finds word]
 P731: "Well, no because 'working' could be used for anything really."
 P732: "True."
 P731: "'Work', no."
 P732: "What about... [scrolls left] 'scheduling'. No, that could be
 News."
 P731: "That could be News, too."
 P732: "What about 'scientist'?"
 P731: "That could be Personal."

What about those users who did *not* stall on *Selection* barriers? Males had a higher tendency of *Hypothesizing* following a *Selection* barrier than females, 26% to 11%. Recall that *Hypothesizing* was coded when the pair discussed a possible fix but didn't include a specific word, whereas *Diagnosing* indicates that the pair specified the word they intended to modify. Thus, males were more likely to follow a *Selection* barrier with a general solution, while females tended to first agree on a word to alter. Why this difference? We know our female participants came into the study with lower self-efficacy than our male participants, and prior research [Beckwith 2007] has revealed female end users to be more risk averse, in general, than male end users. Both low self-efficacy and risk-aversion may have been alleviated by the pair coming to agreement about the best way to proceed; a participant's self-efficacy could be boosted by discovering her partner agrees with her idea, and this improved confidence may in turn lower the perceived risk of the proposed debugging fix. Our approach could use the same solution proposed to help users overcome *Selection* barriers (directing end users toward words which will have the strongest effect on message reclassification) to help low self-efficacy users as well, by reducing the choice of which words to modify down to a more manageable, less intimidating subset.

Like *Selection* barriers, *Coordination* barriers often led to *Diagnosing* (30%) (Figure **Transitions3). Taken together with the other two debugging actions, *Fault Detection* (14%) and *Hypothesizing* (20%), this barrier was followed by a debugging action 65% of the time. Males, however, tended to follow *Coordination* barriers with more *Diagnosing* than females (47% vs. 18% respectively), whereas females followed them with more *Hypothesizing* than males (29% vs. 8%). One interpretation of these results is that

following confusion regarding the impact of their changes, female participants were more likely to step back and attempt to coordinate how their changes will impact the entire system, whereas males tended to stay focused on a specific failure. This would be yet another indication of the comprehensive problem-solving strategy associated with females [Meyers-Levy 1989], providing further evidence of the need to support both comprehensive and non-comprehensive problem-solving strategies in end user debugging environments.

Finally, *Use* barriers (Figure **Transitions4) were strongly tied with a transition to *Diagnosing* (44%); all other transitions were below 15%. It seems that when a *Use* barrier was encountered, our participants' response was to adjust their specific solution, rather than move to a different problem or generalize a solution. This was equally true for males and females. It appears that participants can frequently overcome this barrier by themselves and only need additional help in a few instances.

Thus, our why-oriented approach did not prove successful at reducing the number of barriers participants encountered over the duration of the study. The patterns of barrier transitions is consistent with the Selectivity Hypothesis information processing strategies discussed earlier, adding additional emphasis to the need for intelligent assistant debugging approaches to support both selective and compressive information processing strategies **2.23.

4.3 Results: Information Needs (*What Could Help*)

4.3.1 What Participants Wanted to Know **D1

What information would have helped our participants overcome these debugging barriers? To explore this, we manually compiled a list of every question participants asked during the course of the study, and two researchers iteratively grouped the questions based on the type of information being requested **3.6. This grouping resulted in the seven knowledge bases described in Table **InformationNeeds; the example questions in each category were taken verbatim from participant quotes. The information needs were nearly always in transcript segments that also contained a learning barrier (as described in section **4.1.2). We thus were able to calculate the relationship showing a categorization of participants' verbalizations expressing what they wanted to know when they encountered each barrier. This information is presented via the graphs in Table **InformationNeedsFigure: each graph illustrates the percentage of learning barriers where participants explicitly requested a specific type of information to overcome the barrier **3.6. Figure **InformationNeedCounts shows the frequency of each category.

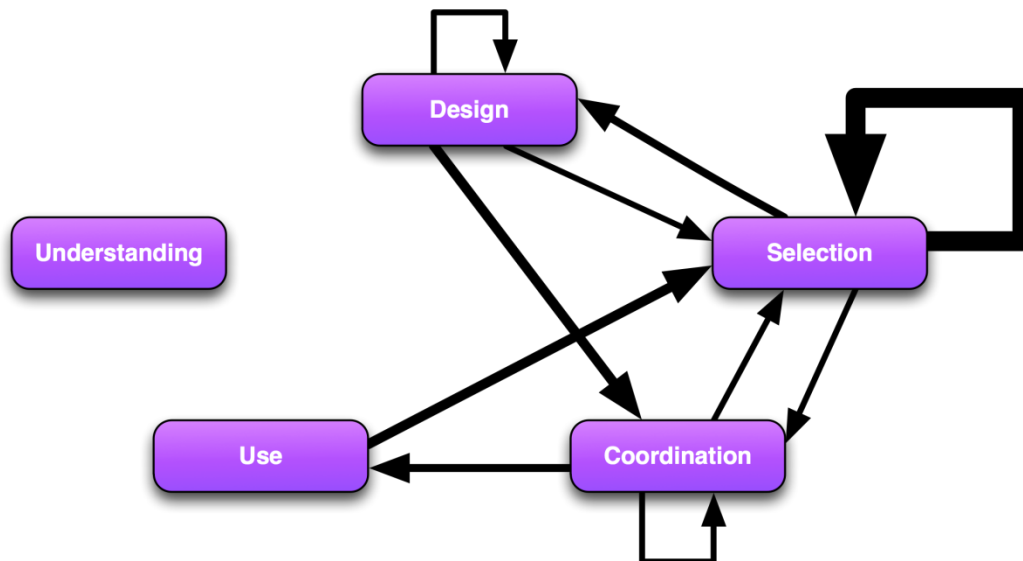


Figure **ExampleTransitions: An example participant pair's path through the debugging barriers. The width of the arrows indicate the percentage of transitions: thinnest = 6%, thickest = 20%. Transitions accounting for 5% or less of the total are not shown.

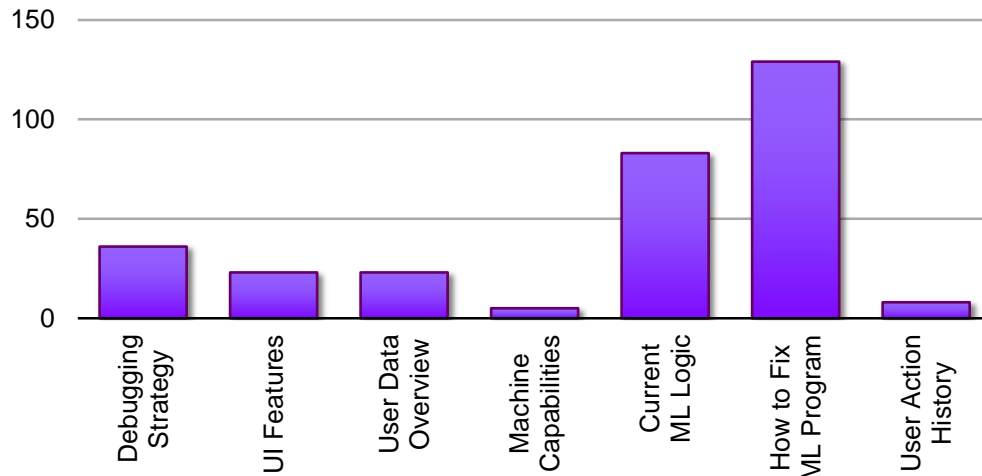


Figure **InformationNeedCounts: The number of times each participant implied a particular knowledge base would help them overcome their current debugging barrier.

As Figure **InformationNeedCounts illustrates, the most frequent information requested by end users was concrete advice about how to fix the machine’s logic. Users wanted to know specifically *which* word weights they should be modifying to move a message into a specific folder, *how much* they should be adjusting the word weights, and previews of *what will happen* after adjusting the weights of particular words. This type of information alone represented nearly half of the total information requests among participants (42% of all requests), suggesting that even satisfying solely this information need may address a large number of user difficulties. Our participants most frequently discussed the value of this information after encountering either a *Selection* (71%) or *Use* (86%) barrier, suggesting that satisfying these information needs through answers to our Why questions could practically eliminate these two barriers.

The second largest set of user-requested information related to the intelligent assistant’s current logic. This includes user questions about *why* the intelligent assistant is behaving in a particular manner, such as “Why did this message turn red?” and “Why won’t this message be filed to *Systems*?”; participants most frequently expressed a need for this type of information after encountering a *Coordination* barrier (74%). This was the primary set of questions we hoped to answer via our Why-oriented debugging approach. Note that, as with the information needs regarding how to fix the assistant’s logic, users appeared to want concrete information; they mentioned specific messages and folders, rather than general questions about how the assistant makes predictions. This desire for

concrete solutions highlighted a nuance in our prototype: it coupled concrete visual explanations of word weights with generalized textual explanations of the assistant’s general algorithm for classifying messages. Participants frequently commented that the generalized textual answers to their questions did not change with context and were unhelpful. For example:

P1001: Ok go to the ‘why’ button. [clicks on the global why menu] Ask ‘why not Systems’. [asks ‘why won’t this message be filed to..?’].

P1002: It says the same thing about word importance.

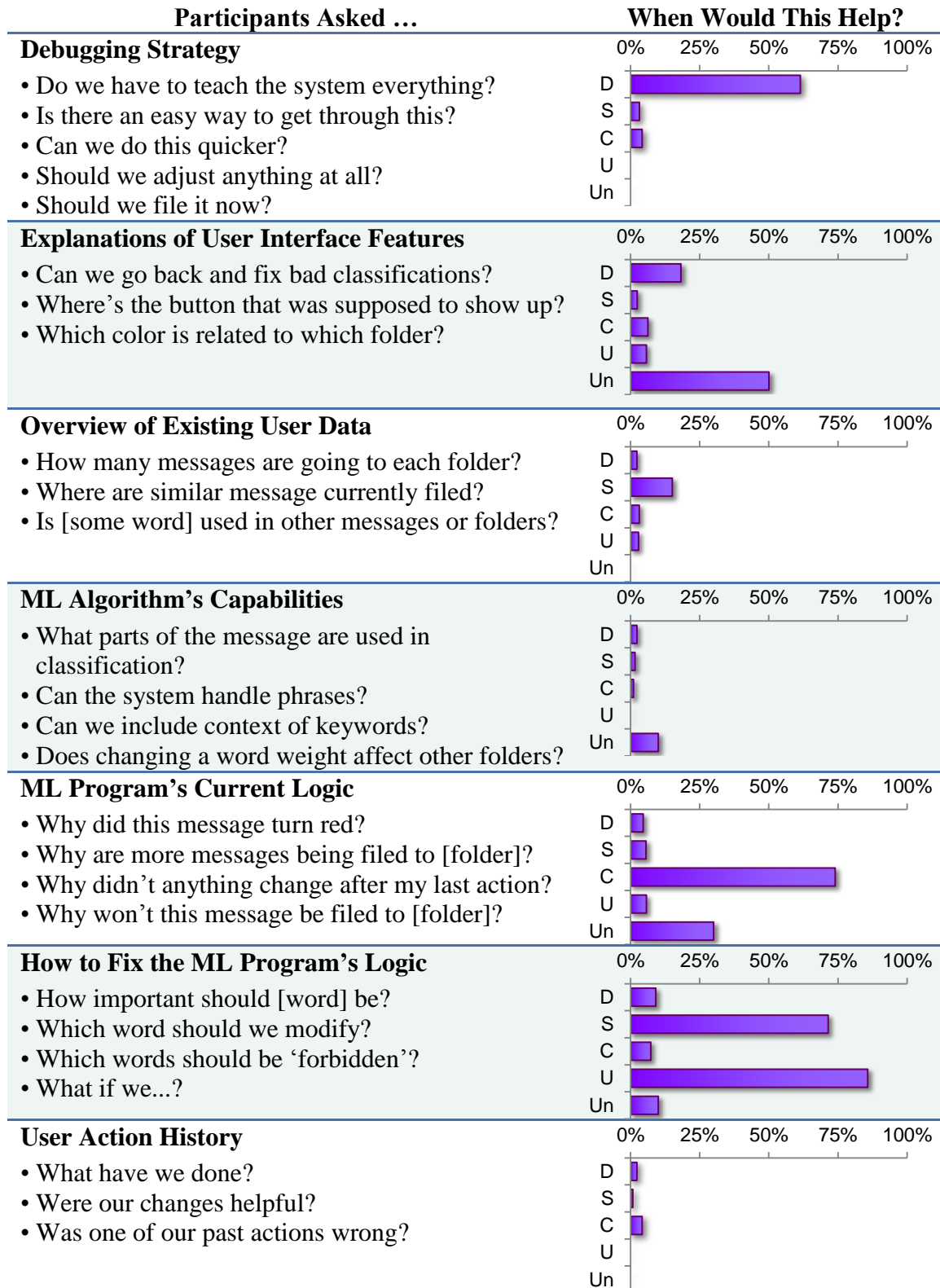
Thus, phrasing the explanation in the context of the message a user is currently working with may be a better way to present this particular type of information.

When participants encountered a *Design* barrier, they frequently believed they could overcome it if they possessed more details about *debugging strategies* (61% of *Design* barriers) ****2.24**. These strategy questions fell into two categories: *general*, when the end user appeared to be searching for a different, better strategy (e.g., “Do we have to teach the system everything?”), and *refinement*, when the user had questions about particular aspects of their current strategy (e.g., “Should we file it now?”). Note that participants expressed more interest in information about debugging strategies than about the *user interface features* of our Why-oriented prototype. Prior research [Kissinger et al. 2006] regarding end-users debugging spread sheet formulas reported a similar difference, and posits that this is part of the phenomenon of “active users” [Carroll and Rosson 1987] who are primarily concerned with completing a task, rather than exploring “potentially interesting” user interface features ****1.5**.

Participants expressed an interest in *overviews of the existing data set* they worked with, such as “How many messages are in each folder?” and “What other messages are [some word] used in?”, a need we also observed in a previous study [Stumpf et al. 2008]. While these only accounted for 7% of observed information needs, a data overview was requested after 15% of *Selection* barriers, suggesting that explanations providing these details may help alleviate the most egregious barrier we observed in this domain ****2.24**. Further, every participant pair save one explicitly requested an overview of the data at least once. Part of the reason may have been due to unfamiliarity with the set of e-mail messages our participants worked with, but even if they had such familiarity, such an

overview could be useful to gauge the importance of words and the distribution of classifications quickly in large data sets.

Table **InformationNeeds: Participants' information needs when they encountered barriers. Graphs indicate the percentage of *Design* (D), *Selection* (S), *Coordination* (C), *Use* (U), and *Understanding* (Un) barriers participants explicitly mentioned needing to overcome each barrier.



The final two information needs, *machine capabilities* and *user action history*, were rare, combining for only 5% of the combined information requests. Even though their occurrence was low, they may have fundamental effects; clearly, a flawed understanding of what the intelligent assistant is capable of parsing and using in its predictions would seriously impair one's ability to provide useful feedback to the program, and a clear indication of the actions a user has performed over time may help end users understand the long-term effects of their changes on the assistant's predictions. The idea of displaying the history of user actions is also consistent with the Whyline approach, since each user-made change to the assistant's logic can impact the classification of multiple messages, and similarly, a single change in classification may be the result of a collection of multiple user adjustments. Explanations of why such a change in classification occurred would be incomplete if they omitted the user modifications contributing to the re-classification.

4.3.2 Gender Differences in Information Needs **D1

Since there were gender differences in the barriers encountered, we also investigated whether there were discernable gender differences in participant information needs that could help overcome these difficulties.

Although our data are sparse, our female participants tended to have more questions about UI features than male participants (Figure **InformationNeedsGender). Previous

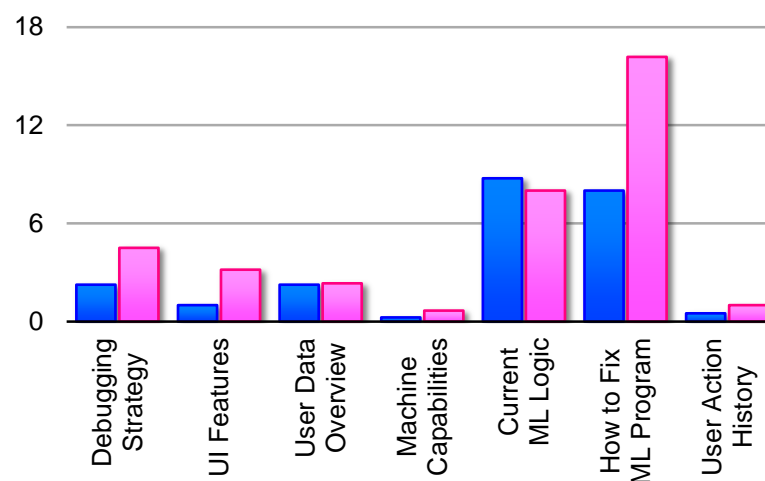


Figure **InformationNeedsGender: Average number of information needs per session encountered by males (dark blue bars) and females (light pink bars).

research [Beckwith et al. 2005] has investigated gender differences in the adoption of debugging features for traditional programs. In that work, females were hesitant about adopting new features; they adopted them less frequently and later in the process than familiar features, and this had repercussion on new bugs introduced through their debugging activities. Our Why-oriented approach introduced a new set of features that are aimed at debugging intelligent assistants. Providing specific support to help understand these features and entice females to use these features may thus be warranted.

An interesting gender difference among our participants was their interest in strategic and tactical information. Figure **InformationNeedsGender illustrates that information about *Debugging Strategy* and *How to Fix the ML Program* was requested twice as much by females as males. Information regarding *How to Fix the ML Program* is particularly applicable for overcoming *Selection* barriers (Table **InformationNeeds), which females encountered almost twice as frequently as males. Moreover, females tended to encounter further *Selection* barriers after the initial *Selection* barrier; providing this information could reduce the risk of females becoming stuck in these *Selection* barrier loops. Furthermore, providing *How to Fix the ML Program* information could help females to overcome *Design* barriers by moving on to debugging activities (e.g., diagnosing, hypothesizing, or fault detection).

Recent work has explored the possibility of using textual and video explanations to present end users with debugging strategies [Subrahmanian et al. 2007]. Such techniques may be especially applicable in this domain because of low user self-efficacy regarding their ability to debug an intelligent assistant, and the inverse correlation we observed between participant self-efficacy and the number of barriers participants encountered. According to self-efficacy theory, watching similar people succeed at the same type of task not only helps guide users toward successful strategies, but may also increase their confidence in being capable of completing the task themselves [Bandura 1977].

In contrast, we did not see gender differences in *understanding* how the intelligent assistant should operate. In our study, female participants requested an overview of existing user data and the machine’s logic and capabilities at about the same frequency as

males, suggesting no gender difference in reasoning about how the classifications should be made by the participants themselves.

In summary, it seems that any gender differences in information needs were more strongly tied to needing explanations about how to strategically make changes than to the specifics of the assistant's logic. Fulfilling these targeted information needs may help to remove the differences in barriers (particularly *Design* and *Selection*) that affected females more than males.

4.4 How machine learning algorithms can better help users (*How*) **D0

If the user and her program are to be partners, each has a role in helping the other cope with difficulties. Our Why-oriented approach allows users to help improve the machine's logic, but how can the machine further help users with their barriers and information needs? We focus particularly on *Selection* and *Coordination* barriers, as these accounted for over two thirds (68%) of the total number of debugging barriers participants encountered during the course of our study.

4.4.1 Helping with Selection Barriers **D0

****TDK to WKW: R2 wants us to discuss other options, such as TF-IDF (comment 2.22)**

Selection barriers were the most frequently encountered type of barrier; in fact, many participants became stuck in loops of repeated *Selection* barriers. Recall that this type of barrier reflects the difficulty of selecting the right words or messages in order to debug the intelligent assistant. This difficulty occurs because a text classifier often uses *all* words appearing in *all* emails as features, amounting to thousands of features. The sheer number of features makes finding a particular word in the source code representation time-consuming for a user. User-interface devices can only do so much to alleviate this problem. For example, our bar graph was scrollable and allowed users to sort the features by weight or alphabetical order. Such interface tweaks are mere band-aids to the real problem—there are simply too many features for end users to consider.

One way to address the *Selection* barrier is to reduce the number of words displayed in the visualization using a class of machine learning techniques known as *feature selection* [Guyon and Elisseeff 2003]. Instead of using all words in all emails as the set of

features, we choose the top K most predictive words as the set of features. Feature selection in our e-mail setting would reduce the number of features from thousands of words down to a few hundred. A particularly useful group of feature selection methods are based on *sensitivity analysis*, which is a technique used in statistical modeling to determine a model's robustness to changes in its parameters [Chan and Darwiche 2002].

Methods for sensitivity analysis are important for addressing *Selection* barriers as they allow us to determine how much the weight of a word needs to be modified in order to change the probability that the email belongs to a folder F . Chan and Darwiche [2002] investigate the sensitivity of probabilistic queries on a Bayesian network in response to changes to a single parameter in the network. The authors then develop bounds on the effect of these changes to the query that allow the machine to determine if a change to a parameter for a word (i.e., the probability $P(W_i | F)$) has little to no effect on the predicted folder. These bounds can also be derived for the naïve Bayes classifier because it is a special case of a Bayesian network. Omitting from the visualization words that have little impact on the current prediction would allow the user to focus attention on only word weights that, if changed for this message, would alter the message's classification. Unfortunately, this approach only captures the effects of a single parameter change. Chan and Darwiche [2004] investigate the effects of changes to multiple parameters, but in the most general case this incurs a significant computational cost.

Although feature selection addresses some of the issues regarding selection barriers, it also introduces other problems. First, reducing the number of words from thousands to a few hundred still leaves the user with a fair number of features to sift through. Second, feature selection determines the top predictive features *using the training set*. If an email should be classified in a folder due to a distinct word that does not appear frequently in the training set, that word is unlikely to be among the top K predictive features. The end user would thus need to be able to add that word as a feature. Allowing end users to create new features is a promising direction for future work.

Furthermore, in the case of sensitivity analysis, even if we can determine the effects of changing multiple parameters, there are still an infinite number of parameter changes that can alter the current prediction to the desired folder. Sensitivity analysis is only useful for determining *how much* a change to the parameters will affect the final

prediction. It is not helpful in identifying *which* changes out of a set of candidates would result in the most accurate classifier for future emails. The underlying issue to support the identification of features to modify is that there are an infinite number of combinations in which the weights on the words can be changed in order to cause the machine learning algorithm to classify an email to the desired folder. Ideally, these changes should improve the classification accuracy of the intelligent assistant not just for the current email message, but also future, as-yet-unseen messages. The distribution of future emails is clearly impossible to obtain; nevertheless, a possible method for helping with *Selection* barriers is to rely on the relationships between words in existing messages, in order to direct the end user's attention to particularly important words. These relationships would need to come from an external source, such as a common sense database [Liu et al. 2003]. For example, if a message was misclassified to the *Finance* folder when it actually belongs in the *Sports* folder, a common sense database could be used to identify words in the message that relate to sports and suggest that the user focus on these words. If, however, the end user's folder assignments for emails are obscure, ill defined, or inconsistent, a common sense database may be unable to help. As such, identifying good features to modify remains a difficult open problem.

Simplifying the visualization by reducing the number of features needs to be carefully balanced against the stated Design Principles of our Why-oriented approach. In particular, we believe that the visualization should not obscure the logic of the intelligent assistant and that the user needs to be able to modify a representation of the source code to debug the program. Both of these principles are at risk if the source code visualization is overly simplified.

4.4.2 Helping with Coordination Barriers **D1

Coordination barriers were the second most frequently occurring type of debugging barrier during our user study. Recall that these barriers concerned how changing logic in one message would affect the system's other predictions, i.e., coordinating how the system responds (or fails to respond) to source code modifications.

The "popularity effect" was a primary source of *Coordination* barriers: the folder with the largest number of filed e-mails dominated the classifier's predictions for the rest of the messages in the inbox. This had the effect that a few participant changes could

(and sometimes did) incorrectly re-classify dozens of messages into the newly popular destination folder. Unfortunately, participants whose strategy was to concentrate on fixing one folder at a time (making the folder of interest temporarily very popular) experienced the popularity effect again and again.

From a machine learning perspective, this popularity effect is primarily caused by the high dimensional nature of the data, the relatively sparse training data, and the class imbalance of the e-mail folders. These factors cause the classifier to overfit both the training data and the participant feedback for the smaller folders. For example, suppose an end user employs the “one folder at a time” filing strategy. He is focused on putting messages into the *Systems* folder, which has keywords such as “Windows” and “McAfee” that are easily identified. Once a large number of messages have been filed to this dominant folder and the classifier learns from the newly acquired training examples, the distribution for the dominant folder will be accurately learned. However, the classifier is poorly trained on the non-dominant folders. In fact, the classifier overfits the training data for the non-dominant folders. Even worse, if the user jumps in to try to debug a non-dominant folder by tweaking an e-mail that belongs in it, the overfitting may be exacerbated more: the overfitting makes all other e-mails seem unlikely to be classified into the non-dominant folders because they must match exactly the under-smoothed distributions for these folders. The classifier then incorrectly files almost all of the e-mails in the inbox under the dominant folder—the popularity effect thereby causing the user’s valid correction to actually make the program worse.

It might appear on the surface that the solution from a machine learning perspective is simply to provide “sufficient” training data for all folders—but applying this solution to e-mail classification is problematic. Many real-world e-mail folders do contain small numbers of e-mails, resulting in sparse training data for e-mail classifiers, and e-mail is known to be “bursty,” i.e., e-mails from a small handful of folders dominate the inbox at certain times. Due to the imbalance in the number of e-mails belonging to each folder, explaining and addressing the popularity effect in domains such as this remains an open problem.

A second major source of *Coordination* barriers was the unexpected adjustment of decision boundaries resulting from participant feedback. ManiMatrix [Kapoor et al. 2010]

tackles this problem by allowing end users to specify which portions of this boundary matter the most to the user’s task; it then adjusts the learning system’s parameters to maximize the accuracy of the classifications the user cares most about. This ability could be beneficial for our Why-oriented approach as well; our prototype showed users the effects of their changes, but did not give participants the choice of specifying the effects they wished to see, and then adjusting the learning system to match the participant’s goals. **2.26

4.4.3 Supporting Answers to the Why Questions Beyond Naïve Bayes **D1

In our study, we illustrated how one particular machine learning algorithm, naïve Bayes, could be used to answer Why questions. Apart from naïve Bayes, many other machine learning algorithms have been used to classify e-mail messages. A natural question to ask is whether other machine learning algorithms can also provide easily understood answers to these “Why” questions.

Answering the “Why won’t this message be filed in <Folder>?” question for folders f and f' requires computing $P(F = f \mid W_1, \dots, W_m)$ and $P(F = f' \mid W_1, \dots, W_m)$. Many machine learning algorithms can provide these probabilities. In fact, a large subclass of machine learning algorithms, known as *discriminative classifiers* [Ng and Jordan 2002], explicitly model $P(F \mid W_1, \dots, W_m)$ and are well-suited to answer this “Why” question.

Some machine learning algorithms may be better than others at providing answers to certain Why questions. As an example, Bayesian networks provide a sophisticated mechanism for providing detailed explanations of how different pieces of evidence influence the final prediction made by the algorithm [Lacave and Diez 2002], but this is computationally expensive. A current challenge for machine learning is to develop answers to Why questions of statistical machine learning algorithms that can be efficiently computed.

5. Conclusion **D0

This paper presented a Why-oriented approach to support end-user debugging of intelligent assistants, in the context of a naïve Bayes learning system for text classification. Our contributions fall into three categories.

First, our Why-oriented approach is the first to extend the successful Whyline debugging approach to machine learning systems. The approach is based on four underlying principles: (Representation-1) representations of both the program logic (“source code”) and execution state must be available and manipulable by end users, (Representation-2) these representations must be faithful and transparent as to what the underlying logic really is (rather than attempting to remove some aspects to simplify it), (ML-1) the explanations must be understandable to end users, and (ML-2) when the end user makes a correction, the machine is required to honor it.

Using these principles, we developed an approach whose essence lies in posing Why-oriented questions and answering them as follows:

- End users can ask *why-questions* of statistical machine learning systems to clarify the program’s current behavior.
- The answers to these why-questions provide faithful explanations of the current logic in terms of representations of the current *source code* and *execution state* of the program.
- These answers can help the end user debug intelligent assistants. Users do this interactively by modifying the answers to make them more correct (from the user’s perspective), which immediately feeds adjustments back to the assistant’s logic.

Our second category of contributions lies in lessons learned for the human aspects of end-users debugging this class of intelligent assistants. Our exploratory study revealed that, although participants were able to use our prototype, every participant encountered barriers while debugging their assistant. The two most common barrier types were *Selection* barriers, in which participants had difficulty selecting the right features (words) or contexts (messages) to modify in order to correct the assistant, and *Coordination* barriers, in which participants wondered how the feedback they were about to give would change the assistant’s other predictions or had trouble coordinating how the assistant responded (or failed to respond) to their modifications. The *Selection* barrier was particularly insidious, often leading to cyclical barrier patterns, and disproportionately affecting female participants. Theories imply some broad-brush attributes for solutions

that try to help users overcome these barriers, suggesting that debugging tools should support both comprehensive and non-comprehensive debugging strategies, and that interfaces should adequately support a wide range of self-efficacy levels and attitudes toward risk. Directions toward specific solutions that might be implemented within these constraints fall within our third category of contributions.

The third category of contributions reveals new open questions for the machine learning aspects of supporting end-user debugging. The first open question is how to provide the information users need to overcome the *Selection* barrier. Regarding this barrier, our participants made clear the information they wish they had—namely which words to concentrate on, how much to adjust each, and what will happen next. Feature selection, such as through sensitivity analysis algorithms, may be promising directions, but it raises as many issues as it solves. However, these issues might be partly addressable by allowing users to create new features and by incorporating knowledge of semantic relationships among words, such as via a commonsense database. Even despite these promising directions, however, automatically identifying good features for the user to modify remains a difficult open problem. Regarding helping the users overcome *Coordination* barriers, many of these were tied to the “popularity effect” that arises in situations of class imbalance, as in email classification. Explaining and addressing the popularity effect in domains such as this one remains an open problem. Methods for allowing end users to specify the desired class distributions may be an alternative solution to this barrier.

In summary, end-user debugging of intelligent assistants is necessary because the end user is the only one with knowledge as to how their own specific adaptation of an assistant should behave. Our Why-oriented approach allows end users to debug such assistants by manipulating their underlying *logic*, not just their predictions. Our empirical results, based upon a prototype of the approach, identify barriers and information needs that end users encountered when debugging intelligent assistants, plus solutions and open research questions as to how to address these barriers and information needs. Ultimately, assisting end users to effectively debug their intelligent assistants opens new opportunities to achieve better and quicker adaption on the part of the assistant, and thus better responsiveness to end user preferences.

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References

- Bandura, A. 1977. Self-efficacy: Toward a unifying theory of behavioral change. *Psychological Review* 8, 2, 191-215.
- Becker, B., Kohavi, R., and Sommerfield, D. 2001. Visualizing the simple Bayesian classifier. In Fayyad, U, Grinstein, G. and Wierse A. (Eds.) *Information Visualization in Data Mining and Knowledge Discovery*, 237-249.
- Beckwith, L. Burnett, M., Wiedenbeck, S., Cook, C., Sorte, S., and Hastings, M. 2005. Effectiveness of end-user debugging software features: Are there gender issues? *Proc. CHI*, 869-878.
- Beckwith, L. 2007. Gender HCI issues in end-user programming. Ph.D. thesis, Oregon State University, Corvallis, OR.
- Burnett, M., Cook, C., Pendse, O., Rothermel, G., Summet, J., and Wallace, C. 2003. End-user software engineering with assertions in the spreadsheet paradigm. *Proc. ICSE*, 93-103.
- Carroll, J., and Rosson, M. 1987. Paradox of the active user, In *Interfacing Thought: Cognitive Aspects of Human-Computer Interaction*, J. Carroll (Ed.), MIT Press, 80-111.
- Chan, H. and Darwiche, A. 2002. When do numbers really matter? *Journal of Artificial Intelligence Research*, 17, 265-287.
- Chan, H. and Darwiche, A. 2004. Sensitivity analysis in Bayesian networks: from single to multiple parameters. *Proceedings of the 20th conference on Uncertainty in Artificial Intelligence*, 67-75.
- Chen, J. and Weld, D. S. 2008. Recovering from errors during programming by demonstration. *Proc. IUI*, 159-168.
- Cohen, W. 1996. Learning rules that classify e-mail. *Proc. AAAI. Spring Symp. Information Access*.

- Compeau, D. and Higgins, C. 1995. Application of social cognitive theory to training for computer skills. *Information Systems Research*, 6,2, 118-143.
- Davies, S. P. 1996. Display-based problem solving strategies in computer programming, *Proc. Wkshp. Empirical Studies of Programmers*, Ablex, 59-76.
- Glass, A., McGuinness, D. and Wolverton, M. 2008. Toward establishing trust in adaptive agents, *Proc. IUI*, 227-236.
- Grigoreanu, V., Cao, J., Kulesza, T., Bogart, C., Rector, K., Burnett, M., Wiedenbeck, S. 2008. Can feature design reduce the gender gap in end-user software development environments? *Proc. VL/HCC 2008, IEEE*, 149-156.
- Guyon, I., and Elisseeff, A. 2003. An Introduction to Variable and Feature Selection. *Journal of Machine Learning Research*, 3, 1157-1182.
- Hastie, T., Tibshirani, R., and Friedman, J. H. 2003. *The Elements of Statistical Learning*. Springer.
- Kapoor, A., Lee, B., Tan, D., and Horvitz, H. 2010. Interactive optimization for steering machine classification. In *Proceedings of the 28th international conference on Human factors in computing systems (CHI '10)*. ACM, New York, NY, USA, 1343-1352.
- Kissinger, C., Burnett, M., Stumpf, S., Subrahmaniyan, N., Beckwith, L., Yang, S., and Rosson, M. B. 2006. Supporting end-user debugging: what do users want to know?. *Proc. AVI*, 135-142.
- Ko, A. J. 2008. Asking and answering questions about the causes of software behaviors, Ph.D. thesis available as Human-Computer Interaction Institute Technical Report CMU-CS-08-122.
- Ko, A. J., Myers, B., and Aung, H. 2004. Six learning barriers in end-user programming systems. *Proc. VL/HCC 2004, IEEE*, 199-206.
- Kononenko, I. 1993. Inductive and Bayesian learning in medical diagnosis. *Applied Artificial Intelligence*, 7, 317-337.
- Kulesza, T., Wong, W., Stumpf, S., Perona, S., White, R., Burnett, M. M., Oberst, I., and Ko, A. J. 2009. Fixing the program my computer learned: barriers for end users, challenges for the machine. *Proc. IUI*, 187-196.
- Lacave, C. and Diez, F. 2002. A review of explanation methods for Bayesian networks. *The Knowledge Engineering Review*, 17, 2, Cambridge University Press, 107-127.

- Lieberman, H. (ed.) 2001. *Your Wish is My Command: Programming By Example*, Morgan Kaufmann Publishers, Inc.
- Lim, B. Y., Dey, A. K., and Avrahami, D. 2009. Why and why not explanations improve the intelligibility of context-aware intelligent systems. *Proc. CHI*, 2119-2128.
- Lim, B. Y. and Dey, A. K. 2009. Assessing demand for intelligibility in context-aware applications. *Proc. UbiComp*, 195-204.
- Little, G., Lau, T., Cypher, A., Lin, J., Haber, E., and Kandogan, E. 2007. Koala: Capture, share, automate, personalize business processes on the web. *Proc. CHI*, 943-946.
- Liu, H., Lieberman, H., and Selker, T. 2003. A model of textual affect sensing using real-world knowledge. *Proc. IUI*. 125-132.
- McDaniel, R. and Myers, B. 1999. Getting more out of programming-by-demonstration, *Proc. CHI*, 442-449.
- Meyers-Levy, J. 1989. Gender differences in information processing: A selectivity interpretation. P. Cafferata & A. Tybout, (Eds) *Cognitive and Affective Responses to Advertising*, Lexington Books.
- Myers, B., Weitzman, D., Ko, A. J., and Chau, D. H. 2006. Answering why and why not questions in user interfaces. *Proc. CHI*, 397-406.
- Ng, A.Y., and Jordan, M.I. 2002. On Discriminative vs Generative classifiers: A comparison of logistic regression and naïve Bayes. In *Advances in Neural Information Processing Systems 14*, 841-848.
- Patel, K., Fogarty, J., Landay, J., and Harrison, B. 2008. Investigating statistical machine learning as a tool for software development. *Proc. CHI*, 667-676.
- Poulin, B., Eisner, R., Szafron, D., Lu, P., Greiner, R., Wishart, D. S., Fyshe, A., Percy, B., MacDonell, C., and Anvik, J. 2006. Visual explanation of evidence in additive classifiers. *Proc. IAAI*, 1822-1829.
- Russell, S. J., and Norvig, P. 2003. *Artificial Intelligence: A Modern Approach*. Upper Saddle River, NJ: Prentice Hall.
- Stumpf S., Rajaram V., Li L., Burnett M., Dietterich T., Sullivan E., Drummond R., Herlocker J. 2007. Toward harnessing user feedback for machine learning. *Proc. IUI*, 82-91.

- Stumpf, S., Sullivan, E., Fitzhenry, E., Oberst, I., Wong, W.-K., and Burnett, M. 2008. Integrating rich user feedback into intelligent user interfaces. *Proc. IUI*, 50-59.
- Stumpf, S., Rajaram, V., Li, L., Wong, W.-K., Burnett, M., Dietterich, T., Sullivan, E., and Herlocker, J. 2009. Interacting meaningfully with machine learning systems: Three experiments. *International Journal of Human-Computer Studies*, 67,8, 639-662.
- Subrahmanian, N., Kissinger, C., Rector, K., Inman, D., Kaplan, J., Beckwith, L., and Burnett, M. 2007. Explaining Debugging Strategies to End-User Programmers. *Proc. VL/HCC 2007*. IEEE. 127-136.
- Subrahmanian, N., Beckwith, L., Grigoreanu, V., Burnett, M., Wiedenbeck, S., Narayanan, V., Bucht, K., Drummond, R., and Fern, X. 2008. Testing vs. code inspection vs. ... what else? Male and female end users' debugging strategies. *Proc. CHI*, 617-626.
- Talbot, J., Lee, B., Kapoor, A., and Tan, D. S. 2009. EnsembleMatrix: interactive visualization to support machine learning with multiple classifiers. *Proc. CHI*, 1283-1292.
- Tullio, J., Dey, A., Chalecki, J. and Fogarty, J. 2007. How it works: a field study of non-technical users interacting with an intelligent system. *Proc. CHI*, 31-40.
- Ungar, D., Lieberman, H., and Fry, C. 1997. Debugging and the experience of immediacy. *Communications of the ACM*, 40, 4 (April 1997), 38-43.
- Vander Zanden, B. and Myers, B. 1995. Demonstrational and constraint-based techniques for pictorially specifying application objects and behaviors. *Transactions on Computer-Human Interaction*, 2,4, 308-356.
- Wagner, E. and Lieberman, H. 2004. Supporting user hypotheses in problem diagnosis on the web and elsewhere. *Proc. IUI*, 30-37.